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Augmented Reality in Maintenance: An information-centred design framework

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Abstract

Augmented Reality (AR) visualization capabilities can impact on maintenance. From enhancing performance to retrieving feedback, AR can close the information loop between maintenance information systems and the operations supported. Though, the design of AR applications is not aligned with current information systems, which prevents maintenance information to be used and improved properly.

In this paper, industrial collaboration contributed to determine a framework for AR integration in maintenance systems. The framework describes information types, formats and interactions modes for AR to enhance efficiency improvements in maintenance of complex equipment. Semi-structured interviews and surveys with maintainers were conducted to determine the maintenance challenges and also to validate the framework proposed. Therefore, exposing future research in topics such as multimodal interaction, information contextualization and performance analysis to achieve the complete integration of AR in maintenance.

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1. Introduction

The maintenance industry is facing significant challenges nowadays. Safety and availability at minimum cost are demanding objectives, owing to the increasing complexity, longer life-cycles and geographical dispersion of the maintained equipment. Therefore, the focus has turned into maintainers and the support given to them when performing their operations. In this competitive context, it is a recurrent challenge for industrial maintenance to obtain and use information [1].

Augmented Reality (AR) is a relatively new form of human-machine interaction that overlays computer generated information (virtual data) on the world environment (real objects) [2]. Since the early 1990s, several AR prototypes have already shown good results in terms of task efficiency, and decrease risk of accidents, demonstrating that this technology can enhance maintenance implementation [3].

Moreover, researchers have identified other applications for AR in maintenance. Performance measurement [4], diagnosis, training or even tools for easy application development (authoring) [5] are some of those in which several studies have focused their efforts. Thus, AR can be useful for many situations in maintenance where users require additional information [6]. Furthermore, if properly used and developed, AR visualisation capabilities can transform maintenance processes. Nevertheless, as AR research in maintenance applications is still at a prototype stage [5], a complete integration of AR in maintenance systems has not been pursued yet.

In this paper, we present an information framework that analyses the information requirements for a complete integration of AR in industrial maintenance systems. It helps to determine the type of data and information to be acquired from and displayed in the AR systems, as well as how to relate it with existing maintenance information.

The paper is structured as follows. Section 2 describes the literature review conducted to examine AR applications in maintenance and the data needed. In Section 3, the industrial challenges regarding information management are investigated through the collaboration with maintenance experts. Section 4 provides an overview of the framework that covers the information requirements of AR integration in maintenance systems, based on academic and industrial challenges. In section 5, the expert surveys conducted to validate the framework are detailed. Finally, section 6 offers the conclusions derived and the subsequent future works proposed.

2. Literature Review

Different authors have already offered state-of-the-art reviews of AR applications in the maintenance industry [4,5,7]. They classify the research proposals based on the maintenance applications (diagnosis, repair tasks, performance measurement, collaborative maintenance, etc.). Apart from the development of hardware and software techniques to improve the effectiveness of AR systems (e.g. better tracking algorithms or real-time sensors interaction), the later authors point out two main areas in AR research to achieve its complete integration in maintenance systems: authoring and context-awareness.

In the AR context, authoring is any development tool that allows to create, edit and update AR contents [2]. In maintenance, the focus has been on providing maintenance experts with no programming skills with the tools to enable the transfer of knowledge [8]. Authoring tools enable to manage existing data in order to display to the maintainer the information required at each step of the maintenance processes. Thus, aiming to reduce implementation costs and obstacles while using existing information and knowledge [9]. However, four main challenges can be found in the literature regarding AR authoring for maintenance:

- **Authoring tools' users and ease-of-use:** the types of authoring and the skills required to use authoring tools are important topics when developing them. Authors like [8] or [9] emphasise on the use of easy GUI's (Graphical User Interface) to generate low-cost applications. While others like [2,10] focus on the type of users (engineers, technicians or maintenance experts) and when they would be able to create content (on-site, online and offline authoring). Nonetheless, when creating authoring tools all researchers stated the need to transfer knowledge as easy as possible, pointing to the use of animations as a type of data to be rendered to maintenance operators.
- **Visualisation challenges:** one of the problems when using animations to explain complex tasks is the rise of visualisation challenges. Problems like occlusion or photorealism have to be considered in order to allocate virtual content in the most effective way [11]. Tools like SUGAR [8] try to solve these problems, considering

different AR techniques for different situations. Thus, it is not only the type of information to be displayed, but also how that is done is something to be considered in general frameworks for AR integration in maintenance.

- **Information display modes:** the creation of content (e.g. animations) for all AR applications is also a challenge. Being able to make use of existing information can help to avoid data duplication and reduce AR implementation costs. Several attempts have been made to generalise the structure of information for different steps of the maintenance processes. From developing frameworks to ensuring consistency of technical documentation [12,13] to adapting content visualised to different maintenance process steps [2,9]. The idea behind still remains the same; to define which information and format to be displayed in order to enhance maintainers' performance.
- **Interaction with the virtual data displayed:** regarding maintainers when creating AR applications, it is also important which types of interactions between users and applications are allowed (e.g. multimodal interaction, gesture interaction, 2D and 3D visualisation, text, etc.) [6]. [14] describe the options available and their capabilities. While others like [15], research new forms to explore transformations of maintenance (e.g. remote maintenance or collaborative tele-assistance with authoring capabilities). From a data management perspective, the type of interaction would modify how the data should be displayed but also what data can be captured from maintainers when using the AR applications.

Apart from managing the existing data, as pointed out by [2], AR maintenance solutions should be more than just an advanced visualisation tool, hence the display of the virtual information should be adapted to the specific context of the technician. That is similar to the definition of context-awareness given by [16]: "A system is context-aware if it uses the context to provide relevant information and/or services to the user, where relevancy depends on the user's task". Thus, AR solutions for maintenance should be context-aware, to use not only existing data but also to acquire and analyse data from the environment in order to adaptively help maintainers in their tasks (diagnose, repair, perform, etc.).

Based on the literature, two main types of data can be acquired from the environment in order to adapt existing information for enhancing maintenance operations:

- **User data:** most authors describe the need to adapt maintenance information to the maintainers [2,17] depending on their skills. Also, they agree on proposing ontology-based rules to define several levels of guidance [6] or used different data formats to display the information required [16]. Nevertheless, the main idea is to make AR systems adaptive to users; that, combined with different types of interaction can enhance the use of AR for performance measurement [18].
- **Environmental data:** different types of AR applications for maintenance require different types of data to be acquired from the environment. For example, information for enhancing maintainers' diagnosis should be contextualised with real time data from equipment sensors. However, context data can be classified and utilised at different levels to contextualised information and provide reasoning and analysis [2,16].

Therefore, several research gaps have been identified from the literature:

1. There are no frameworks that identify the information within AR that can be integrated in maintenance systems. These should identify the information format and context.
2. There is a need to define the contextualisation of the information in these frameworks. It should be based on data acquired from the environment, the situation, the user, and the relations between them.
3. There is a need to also consider the interaction between AR systems and users within these frameworks. It should identify additional data to enhance system's outcomes.

Consequently, the information frameworks defined for AR integration should make AR systems adaptive and intelligent.

3. Industrial Challenges in Maintenance

In order to properly define maintenance operations, it was necessary to engage industry this research. Thus, four one-hour interviews were conducted to discover the main maintenance challenges with two maintenance experts and two technicians, who had an average of 20 years' experience in the military maintenance industry.

Semi-structured interviews were conducted with current maintainers and maintenance experts to discuss the challenges they found in maintenance processes and their root causes. The collaboration resulted in the identification of the key challenges in these processes where AR could help. Figure 1 presents the maintenance challenges recognised, its consequences and its root causes or triggers.

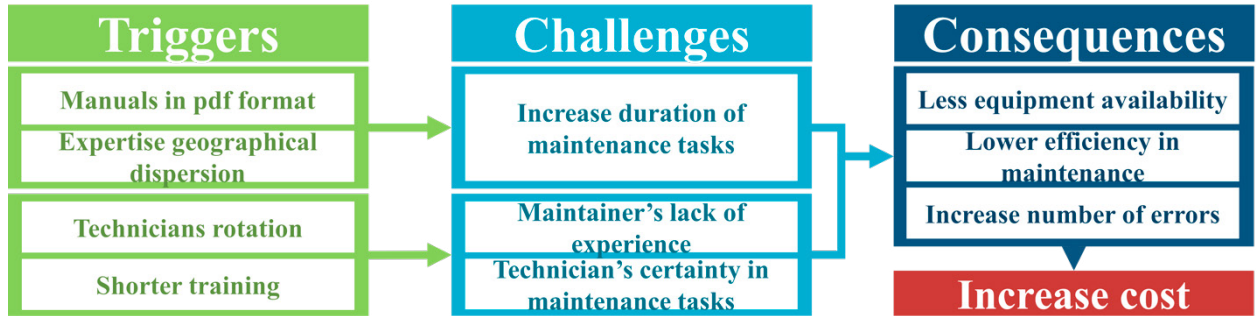


Figure 1. Maintenance challenges, consequences and root causes detected within maintainers' operations

The main challenges identified are all related with maintenance tasks/operations (either repairing or diagnosing). Besides, looking to the triggers, it can be seen that the current support given to the technicians is not always enough for the complex tasks they perform. Nevertheless, if the errors continuously increase and the performance decrease (consequences) that means continuous improvement tools are neither used nor exist. From a data point of view, the conclusions extracted from the figure are summarised in the following list:

1. Diagnosing and maintaining are the processes considered by maintainers. However, there weren't reporting processes which also considered measuring their performance in those. Therefore, also performance analysis should be considered as a process to be covered within maintenance.
2. The supportive information given is not delivered properly (neither visual nor adapted enough); and so, the technicians are not able to interpret it correctly.
3. The information that can be acquired from maintenance processes is not correctly managed or analysed in order to improve their performance (through continuous improvement loops).

Either when the information has to be visualised by technicians or when the information has to be acquired for performance analysis, the conclusions identified in this research led to describe the information required to support each type of maintenance processes by using AR.

4. AR Information Framework for Maintenance

Based on the previous research, it can be said that one of the main reasons why AR has not been widely applied in maintenance is the consideration of data management on the design of AR applications. If maintenance information is appropriately delivered and feedback data accurately acquired, then the gaps identified within the industrial challenges can be addressed. Thus, combining the gaps from the literature review with the challenges from the industrial collaboration, the information requirements for AR integration in maintenance processes can be determined.

Table 1 summarises these requirements, which refer to the gaps and challenges identified in sections 2 and 3, respectively. Based on those, we can propose a framework to close information gaps in maintenance systems. That means, to establish the foundation to develop adaptive and intelligent AR systems that cannot only support technicians, but also analyse their performance and recommend improvements.

Table 1. Information requirements for AR integration in maintenance systems

id	Academic gaps – section 2	id	Industrial challenges – section 3
1	Information design requirements for AR: type, format and context.	1	Maintenance operations to consider in AR design: diagnosis, repair and performance analysis.
2	For information contextualisation consider technicians and equipment.	2	Avoid textual delivery of information and promote more visual formats.
3	Consider user-information interaction for proper contextualisation.	3	Acquire/manage data for performance analysis.

First, we classify the information required and its main characteristics for each maintenance process (diagnosis, repair and analysis (performance measurement)). Then, we structure this classification to create the framework for AR maintenance information. Table 2 describes the initial classification of information; also including the recommended type of interaction in order to define the type of AR techniques required.

In order to enable the display and acquisition of the information types proposed (instructions, health condition and performance time and errors), several AR capabilities are required. That means, other types of data (such as image tracking data or technician gestures) are required to develop the consequent AR systems. Those are also considered in the information framework, which is presented in Figure 2.

Table 2. Maintenance information needs - formats and content classification

	Authoring		Context-Awareness		Interaction
Repair	Information	Instructions	Context	User-centred	3D and 2D visualisation
	Format	Animations and text	Data	Maintenance skills	
Diagnose	Information	Equipment's health condition	Context	Equipment-centred	3D and 2D visualisation
	Format	Coloured 3D models and text	Data	Sensors' information	
Analyse	Information	Performance time and errors	Context	User and equipment centred	Gesture interaction and 3D visualisation
	Format	Text	Data	Sensors' information	

The information framework (Figure 2) proposes an integration model for AR in maintenance. It describes the links between the maintenance processes (light blue arrow) and the maintenance information systems and environment (grey boxes) that enhance those processes using AR visualisation and interaction abilities. This is driven by the data required to achieve it, which comprises information formats, AR capabilities and environmental data (respectively orange, green and dark blue boxes that refer to Table 2).

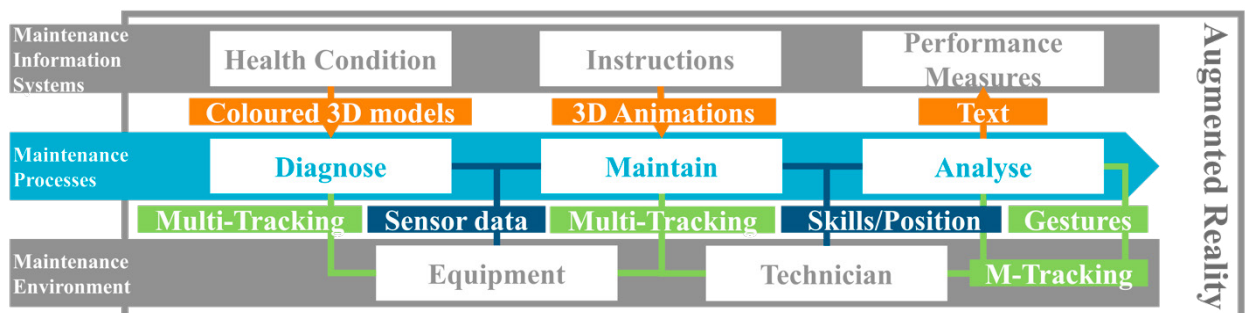


Figure 2. Information framework for AR integration in maintenance systems - Information to overlay and retrieve

The three maintenance processes considered in the framework are diagnosis, repair and analysis. For diagnosing, the framework proposes to use 3D coloured models based on the sensor data of the equipment tracked to help maintainers diagnosing faults occurred. Then, the same data can be used to assess whether the technicians performed the diagnosis correctly. For repairing, 3D animations are used to easily explain the repairing steps of the equipment tracked. Furthermore, in the case of analysing technicians while repairing, also gestures can be tracked to assess their performance. Furthermore, the performance data captured while analysing diagnosis and repair processes could be used to improve the processes and the data that supports them.

Depending on the capabilities provided by different AR systems. This framework enables to develop AR maintenance applications with different levels of immersion and interaction between virtual and real world. Thus, the more interaction between the two, the more data will be acquired and the more knowledge that can be transferred between users and systems.

5. Expert surveys: Framework validation

The finalised framework needed validation from industry, in order to analyse whether it can be integrated into existing maintenance systems and can add improve maintenance processes. Thus, four interviews with different maintenance experts were conducted to ensure the information provided covers the information needs of technicians in maintenance operations. Those were semi-structured interviews based on the use of a questionnaire. It covered the following topics regarding the information completion, enhancement of maintenance processes and maintainers' usability of the resulted AR applications:

- **Maintenance Processes:** to define to what extent the information was aligned with tasks carried on during diagnose, repair and analysis operations.
- **Maintenance Performance:** to analyse how the information could improve maintenance performance by enhancing maintainers' abilities.
- **Maintenance Analysis:** to analyse to what extent the data captured from performance can help to improve maintenance knowledge.
- **Maintenance Information Framework:** to define to what extent the information framework provided covers all information needs from technicians.
- **User-Information Interaction:** to analyse if the user-information interactions proposed enabled sufficiently data capture and analysis.

The questionnaires included several statements about each topic, allowing the experts to reply about their agreement with them using a 1-5 Likert Scale. Their results are provided in Figure 3.

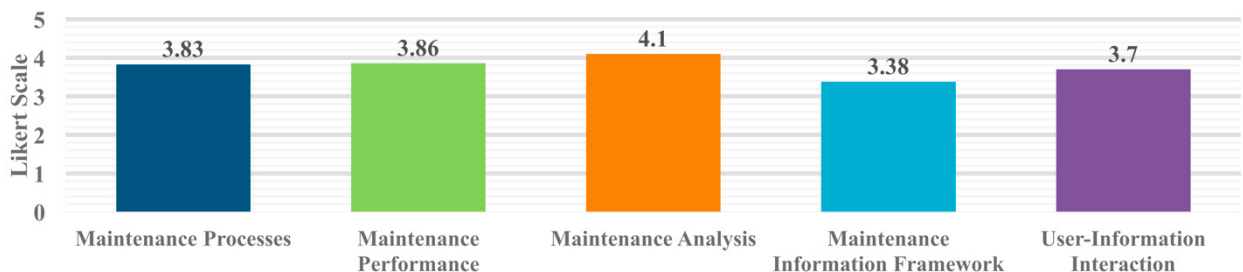


Figure 3. Survey questionnaire results

The results given in the figure above presents an indicative validation of the framework proposed for integrating AR in maintenance. Nevertheless, some comments regarding the validity and scope of these results can be made:

- The interviewees marked the framework above average in all the topics. Hence, it can be said that they agreed with the framework's AR-integration proposition. It can also be said that these marks reflect the alignment between the framework and the industrial challenges identified.
- The relatively higher result regarding the maintenance analysis topic can be considered as an indicative to point out performance analysis as a necessary application for AR systems in maintenance.
- These are the results of a limited number of interviews (four). Even though they denote that the framework is valid for AR integration in maintenance, more interviews should be made to pursue an overall validation.
- These interviews are focused on an industrial sector (military). Even though the results indicate validation in this sector, overall validation should be pursued with experts from different sectors. Thus, it could be studied whether there exist differences between sectors for such a framework.

6. Discussion: AR Integration in Maintenance

The framework validated in the previous section proposes an information-centred design approach for AR systems to achieve their integration in maintenance. Nevertheless, this is a topic that has not been widely researched yet. Several reasons from the insights of this paper are discussed in the following:

- AR research is still quite immature [5].
- Regarding maintenance applications [4,5,7], this has led AR research to focus on maintenance processes (such as diagnosis or repair) one by one, with no consideration of AR applications to cover all maintenance processes.
- In order to design a system for AR in maintenance, both topics (AR and maintenance) have to be considered hand-in-hand regarding data management. That means, it is needed to analyse why the information is required, how it should be captured or visualised and how it can be managed within existing maintenance information systems.
- Thus, if data frameworks are defined, AR could keep focusing on developing the capabilities required to achieve the data relations required. Also considering the connection with other technologies that are already applied or will be in the near future in maintenance systems.

Therefore, there exists the need to redefine conceptually the design of AR systems for maintenance. The focus should be on why data is needed, what it is needed and how it should be acquired/managed, and what challenges it is addressing. That is also the reason why this framework can contribute to enhance AR integration from both, academic and industrial perspectives. On the industrial side, this framework can be used as a basis to develop real-life applications and detect the needs of resources for it. On the academic side, it establishes general rules (e.g. data formats) for development of AR applications that can be used within research to make studies comparable. It also helps to identify several research directions to increase the level of maturity of AR technologies for maintenance applications.

7. Conclusions and future work

This paper has developed an information framework to enable the integration of AR in existing maintenance systems. The proposal given considers the general implementation of AR in maintenance processes (diagnose, repair and analysis) from a data management perspective. That means, the framework describes the information to enhance performance and knowledge of maintenance processes and the AR capabilities to manage, acquire and display that data properly.

The expert sessions' results indicate that this framework helps to integrate AR in maintenance systems. Nevertheless, further research is required about the capabilities AR can provide to acquire and analyse distinctive data in order to improve maintenance operations.

To summarise, this paper concludes that the framework proposed offers a holistic view of AR integration in maintenance systems and the subsequent advantages and challenges from this consideration. Thus, identifying general rules for AR research replicability in maintenance applications and future research directions.

A number of future work suggestions can be made. First, further validation interviews with maintenance experts from different sectors are required to overall validate the framework within maintenance. Second, multimodal interaction methods should be investigated to track the interaction between real world objects; that means, to enable AR systems to analyse when the equipment is repaired and how was the repair performed. Third, AR systems should be complemented with analytic tools that can provide recommendations based on the previous interaction analysis. And so, maintenance knowledge could be improved. Fourth, integration with other technologies should be analysed in order to achieve the capabilities required. Fifth, further contextualisation (either with user or equipment data), using for example ontology-based rules [2], should be provided to increase AR visualisation and analysis capabilities. Therefore, the information frameworks that outcome from those researches could make AR systems adaptive and intelligent; and this could enable the transformation of current maintenance systems.

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